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Virtual mapping of reference conditions of pollutant load in waterbodies: phosphorus in the Lake Peipsi basin

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Our study proposes a novel virtual mapping method to define reference conditions in a water body that is assumed to be not affected by human activities. We applied a modified PolFlow model, a raster-GIS analysis tool, to the Lake Peipsi basin. Running 'reference conditions' scenario revealed that the mean annual reference load comprised 225 t (31%) of phosphorus while the remaining 498 t (69%) originated from anthropogenic sources. Of the total reference load, 77 t (34%) originated from the Estonian part of the catchment, while the remaining 148 t (66%) came from Russia. High variability appeared in key factors that determine the P load to the lake in Estonia and Russia. The management measures in Estonia should prioritize land use issues, such as a reduction of diffuse emissions from agriculture. In contrast, the short-term Russian policy should focus on improved municipal and industrial waste-water treatment.

Introduction

The global, chemical pollution of natural waters affects aquatic life and human health (Schwarzenbach *et al*. 2010). To combat water pollution, the EU Water Framework Directive (WFD 2000), among other, aims to achieve concentrations of nutrients that 'do not exceed the levels established so as to ensure the functioning of the ecosystem'. Such a 'good nutrient status', according to the directive, is a rank lower than 'reference conditions', representing 'high ecological status', requiring that nutrient concentrations remain within the range normally associated with undisturbed conditions.

WFD allows reference conditions to be established in different ways. In the case of availability of undisturbed or minimally disturbed catchments, reference conditions and human impact can be revealed from their comparison with other, disturbed catchments. However, in a time of possibly anthropogenic climate change, it is hard to argue that anywhere in the world could remain strictly undisturbed. Of 'minimally disturbed' catchments, the only places left tend to be smaller or upland systems which fail to supply reference targets for the larger or lowland waterbodies (Thoms *et al*. 1999). Therefore, the definition of reference conditions requires application of other methods such as the use of historical and palaeoecological data or modelling. May *et al*. (2005) recommended the 'export coefficient modelling approach', relating historical land cover with P export values (kg ha^{-1}). The SWAT model (Arnold *et al*. 1990), which is widely applied for river basin management

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worldwide (Gassman *et al*. 2007), also considers weather, soil, topographical information and vegetation data in addition to land cover.

The above-described modelling approach relates the concept of reference conditions with historical times when human impact on waters was relatively low. However, as usually the chosen reference period is post-industrial (Carvalho *et al*. 2005), the modelled reference conditions in fact suffer from significant human impact. Moreover, due to climate change and introduction of invasive species, for example, these historical undisturbed, non-impacted conditions cannot be restored. Mao and Richards (2012) concluded that the decline in water quality may, in principle, be irreversible because it is impossible to eliminate or mitigate external stress in appropriate ways. Recovery programmes have rarely brought water quality to a predefined state. Hence, in practice, water quality is irreversible and the historical conditions cannot be a recovery target. Therefore, using historical references as the management goal for the water quality standard may generate unrealistic expectations (Dufour and Piegay 2009). Yet, water quality management requires clear goals. Instead of looking at historical times, we need to set reference conditions in the context of the present.

A widely used alternative approach to historical conditions is hindcasting. For instance, Dodds and Oakes (2004) used the analysis of covariance within ecoregions as categories and percentage of anthropogenic land use as covariates to predict reference nutrient concentrations. However, their report admits several limitations of this regression model. First, it does not quantify all sources of human impact such as point discharges, nor is the regression approach able to assess the in-channel transformation of nutrients. Another limitation for such a method is the fact that land cover is never entirely natural or anthropogenic. Dodds and Oakes (2004) accounted that urban land and cropland are solely anthropogenic. However, in the context of P loss, other land cover types may also have significant anthropogenic impacts. For instance, drainage of forests and wetlands, clearcuts and peat mines are land uses that were overlooked. Therefore, the regression approach probably overestimates the natural load of nutrients.

Instead of a statistical approach, our study aimed to create a virtual catchment area with no human impact. Since the anthropogenic load of pollutants originates from various point and diffuse sources, we set up a GIS model to quantify the relevant links. The first modelling step, therefore, created a model of actual (= present) conditions in a drainage basin, relating the load and concentration of pollutants in water bodies with waste water discharge data, land use and other human pressures. The second modelling step generated a virtual situation of reference conditions in which all human activities are removed. Using the quantitative linkages from the first step, the model provides a reference load and concentrations of pollutants. Our study projected reference conditions of P load and concentration in a large river basin, by removing all agriculture, industry and even population. Setting such reference conditions also enabled us to assess the rate of human impact, apportionment of various sources and, therefore, the adequacy and compatibility of reduction targets and management measures.

Study area

The study area involved the Lake Peipsi (Chudskoe) basin (Fig. 1). Its surface area of approximately 3550 km^2 makes Peipsi one of the largest European lakes. The lake and its basin drain via river Narva to the Gulf of Finland (Baltic Sea). The lake is shallow, reaching 15 m in the deepest part. The lake contains 25 km^3 of water which resides there for about 2 years (Jaani 2001). Of that water, 82% flows in through streams while remaining 18% precipitates directly to the lake surface.

The Lake Peipsi drainage basin, 44 725 km^2, exceeds the lake surface in size by 12 times. The basin area is divided between Russia (59%), Estonia (33%), Latvia (8%) and Belarus (0.3%). The largest sub-basin is the Velikaya river basin, which drains approximately 58% of the whole Peipsi drainage basin.

Forests and semi-natural areas dominate in the Peipsi basin (Table 1). Agricultural areas cover around 14%. Wetlands, although scattering the entire basin, are located in a relatively large portion near the shore of the lake.

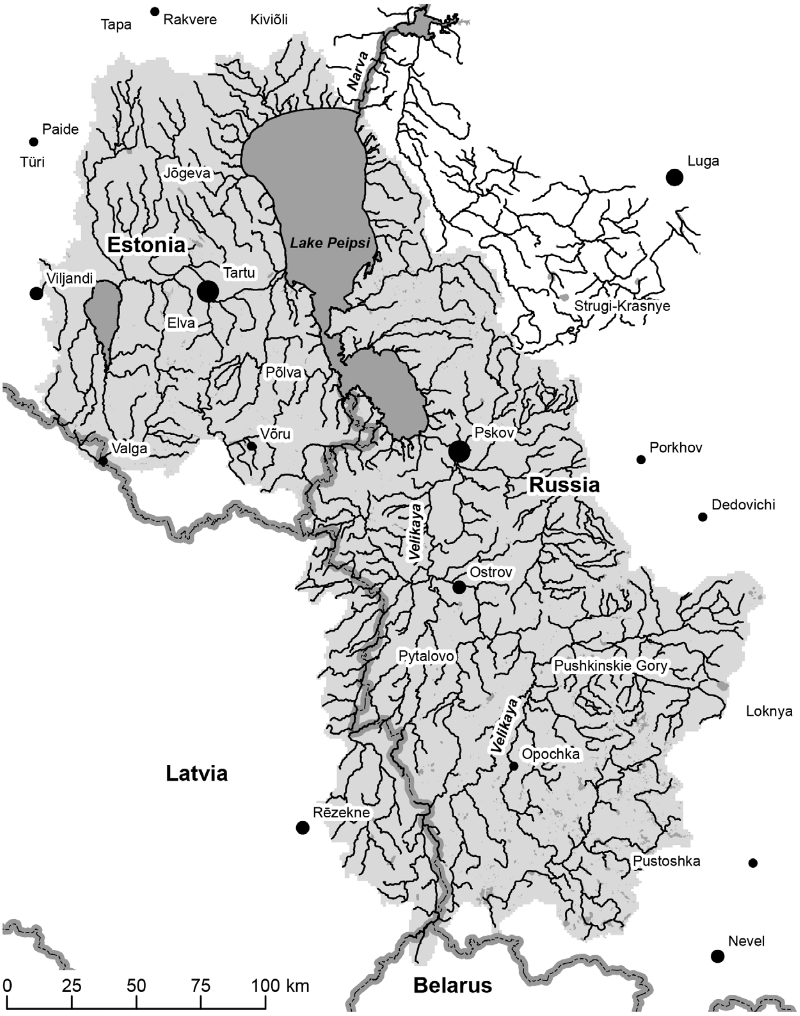

Fig. 1. Lake Peipsi drainage basin.

The drainage basin is flat, with a highest point of 338 m a.s.l. and an average elevation of 90 m (modelled from Hannerz *et al*. 2002). This is typical of north-European lowland area of glacial origin bases on Paleozoic bedrock, covered by unconsolidated materials.

The mean annual air temperature in 1987–2004 in Tartu (Estonian part of the catchment) was 5.8 °C, rising 0.4° per decade while precipitation in 1976–2004 was 1.76 mm day^{-1} (Nõges *et al*. 2010).

The main environmental problem in Lake Peipsi is progressing eutrophication, caused mostly by nutrient input through rivers from the catchment area. Due to rather low N/P concentration mass ratio (less than 10:1), N_2-fixing cyanobacteria, such as *Gloeotrichia echinulata*, *Aphanizomenon flos-aquae* and *Anabaena* sp., perform massive blooms (Nõges *et al*. 2007). In order to improve the state of the lake, there-

Table 1. Land cover types in lake Peipsi catchment area (from EEA 2006).

	Area (km^2)	Percentage
Artificial surfaces	302	0.6
Agricultural areas	13392	27.8
Forests and semi-natural areas	28582	59.2
Wetlands	1638	3.4
Water bodies	4342	9.0
Total	48256	100

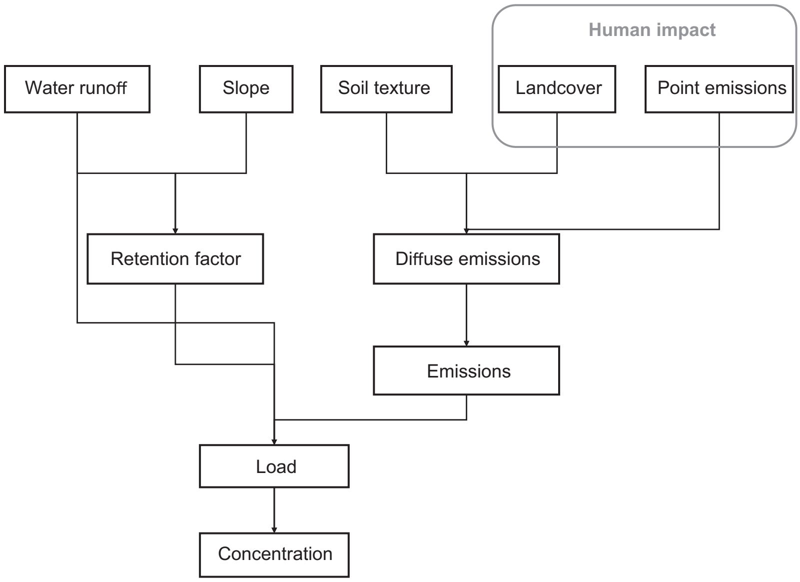

Fig. 2. Prediction of the phosphorus load and concentration in the Lake Peipsi basin (excluding the lake itself), depending on land cover and point emissions resulting from the PolFlow model.

fore, requires a significant reduction of the P load. The southern and shallower part of Peipsi, Lake Pihkva (Pskov) suffers from much higher anthropogenic pressure than the northern part, Peipsi *sensu stricto*. Therefore, hydrochemical and phytoplankton data indicate a mainly moderate ecological quality in Lake Peipsi.

The net annual load of P to Peipsi in 2006–2010 was 723 t (results from this study). Roughly half of that was retained in the lake while the other half flowed on to the River Narva (estimated from Kondratyev 2011). Pskov (Russia) and Tartu (Estonia) with 206 000 and 100 000 inhabitants, respectively, contribute the majority of the point source pollution (Buhvestova *et al*. 2011).

Methods

The PolFlow model (de Wit 1999; Mourad *et al*. 2006) based on the PC Raster GIS model software was applied to establish the reference load of P into the Lake Peipsi basin, excluding the lake itself. The model details large scale (both in time and space) processes such as population dynamics, urbanisation, economic growth, agricultural development, etc., and their impacts on water quality. For instance, in a previous application, Mourad *et al*. (2006) translated various economic development scenarios to the scenarios of population numbers, wastewater treatment, fertiliser use, livestock amounts, crop yields, atmospheric deposition and the area of agricultural land. Using that input, the model calculated future load values.

The modelling approach consists of a full-raster GIS-embedded set of sub-models, programmed in the PCRaster GIS dynamic modelling language (Wesseling *et al*. 1996). The time step of the PolFlow model is 5 years and spatial resolution is 1 km^2. The model has been previously employed for the Lake Peipsi basin to assess various nutrient load scenarios (Mourad *et al*. 2003).

In this study, five-year annual average load of P to Lake Peipsi in 2006–2010 was calculated, based on point and diffuse emissions to surface waterbodies as well as retention in the catchment (Fig. 2). Bulk diffuse emission parameters ('export coefficients') were applied according to CORINE, the land cover and soil texture data (Table 2). Mean area diffuse emission parameters for a year with long-term mean precipitation and water runoff were determined according to measured and/or estimated emissions from various land cover and soil types as described in Oras *et al*. (2006; *see* Table 2). The calculated parameter values based mostly on long-term intensive water-quality observations in eight small Estonian agricultural (including two automatic monitoring stations), five forest and five wetland catchments. However, we considered also other reports from other countries around the Baltic Sea. The calculated agricultural load includes the load from the scattered dwellings not connected to sewage water system.

The calculation of urban storm-water pollution load was based on storm-water-runoff pollutant concentrations and annual precipitation. The annual load was determined separately for high-density residential, low-density residential and industrial/commercial areas. It was also estimated that the fraction of annual rainfall events that produce runoff is 0.9. The runoff coefficient for high-density residential, low-density residential and industrial/commercial area were determined to be 0.60, 0.25 and 0.72, respectively. The runoff coefficient was determined from the percentage of impervious area as described by the methods of Schueler10. The percentages of impervious cover were determined to be 65%, 25% and 85% for the high-density residential, low-density residential and industrial/commercial areas, respectively.

The emission sub-model was not calibrated. The only calibration component in the model was the retention of P in surface waters which was calculated and calibrated according to de Wit (1999). The chosen standard for calibration was the Estonian national river quality monitoring database (EEIC 2012b), covering 29 stations, five years from 2006 to 2010, providing P concentration values from monthly samplings. However, 23 of these stations were left out from the calibration due to small catchment size. As the PolFlow model was successfully validated for catchments larger than 1000 km^2 (de Wit 2001), we calibrated the model only against five-year average P concentrations at the remaining six stations, catching water from at least 1000 km^2 as:

$$t_{\mathrm{f}} = 1 - \frac{1}{1 + \left\{ \left[\mathrm{rn}_1 \left(1000S + 1 \right) \right] Q^{\mathrm{rn}_2} \right\}}$$

where t_{f} is the transport fraction of the grid cell (km^2), S is the slope gradient and Q is the average annual discharge (m^3 s^{-1}). The parameter rn1 adjusts the significance of the slope gradient while rn2 adjusts the significance of discharge. The calibration of these two parameters resulted in 100 s m^{-3} and 0.2, respectively. However, a special retention parameter was applied and calibrated for lakes. Resulting from the spatial resolution, the calculation of P retention was possible for the streams with catchment size of at least 1 km^2.

For the calculation of annual average flow-weihted P concentration, a static hydrological sub-model, established and calibrated by Mourad *et al*. (2006), was applied to estimate 5-year average total runoff (i.e., precipitation minus evapotranspiration), based on soil and landscape factors (terrain slope, soil type, land cover, drainage network density, and aquifer type). Evapotranspiration was estimated as a function of land cover class. The outcome of this sub-model includes annual average water runoff in surface waters which, being divided from the load of P, revealed concentration of P.

Table 2. Applied emission parameters and natural scenario depending on various land cover types.

Land cover	Emission of P (kg ha^{-1})	'Natural' scenario
Artificial surfaces	0.25	Forests
Arable land	0.4 (clay soils: 0.8)	Forests
Permanent crops	0.12 (clay soils: 0.24)	Forests
Pastures	0.2 (clay soils: 0.4)	Forests
Complex cultivation patterns	0.3 (clay soils: 0.6)	Forests
Land principally occupied by agriculture	0.2 (clay soils: 0.4)	Forests
Forests		No change
Sandy and loamy soils	0.06	
Peat and clay soils	0.1	
Shrub and/or herbaceous vegetation associations	0.12	No change
Open spaces with little or no vegetation	0.12	No change
Inland marshes	0.11 (coastal reed belts: 0)	No change
Peat bogs	0.09 (peat mines: 0.38)	No peat mines

Two modelling scenarios were developed: 'actual' scenario that represents the real load of P in the present time, and the 'natural' scenario, which represents the background load within reference conditions. To project such a natural load, a theoretical scenario was established with no human activity in the entire catchment area. Such a scenario, hence, lacks point pollution sources. Instead of involving agricultural and urban land, the entire drainage basin consists of only natural surfaces. In defining such a natural scenario, agricultural and urban areas in the land cover map were replaced by forest (Table 2) and peat mines by natural bogs.

The comparison of 'actual conditions' and 'reference conditions' scenarios provided the rate of anthropogenic load of P into the lake. Source apportionment of that load prioritized the areas of promising load reduction efforts.

Data

The GIS data were acquired from various sources (Table 3). The Russian and Latvian point emission data were estimated based on the population data. Industrial and municipal total emission of 0.7 kg P yr^{-1} per capita was derived from WRS Uppsala AB, and removal of 20% by waste water treatment was assumed. The pollution load of P from Estonian point sources was obtained from the national water use database, based on the annual reporting of water users. The frequency of the self-monitoring of waste water effluents is 4–12 times a year and involves all facilities covered by the water use permits. Most of the point sources load is transported to Lake Peipsi via rivers. The point-source P load to the lake from the Estonian part of the catchment shows a remarkable decreasing trend since the beginning of the 1990s. Considerable efforts were made to raise the performance of wastewater treatment plants in the catchment, which was the major reason for a decrease of more than 75% in the P point-source load to recipient waterbodies between 1994 and 2012 (EEIC 2012a; Fig. 3).

Results

The model calculated annual average emissions of P to surface waters in each km^2 of the Peipsi basin, excluding the lake itself. Then, the model revealed retention of P in each segment (1 km) of the surface waters, resulting in a net load, including load to Peipsi. A water runoff module enabled calculation of annual average flow-weighted mean concentration in each stream segment.

The slope of the regression between simulated and measured concentration values (the intercept set to 0) was 1.03 while the coefficient of determination (r^2) 0.56. Predicted/observed data ratio (E) was 1.04 while the logarithmic transformation variable (e) was 0.038 (calculated according to Moriasi *et al.* 2007). The mean absolute error in predicted loads, compared against monitored loads, was +3%.

The total modelled mean gross load — equal to total emissions — of P into the Lake Peipsi drainage basin in 2006–2010 was 930 t. Of that amount, 207 t (22%) was retained in the network of streams and lakes. The remaining 723 t P yr^{-1} loaded Lake Peipsi (Fig. 4). The total annual

Table 3. Used spatial data sources.

Data	Source
Long-term annual average water runoff	Mourad *et al.* 2003
CORINE land cover	EEA 2006
Elevation	Hannerz *et al.* 2002
Point sources, Estonia	EEIC 2012a
Monitored concentrations of P in rivers	EEIC 2012b
Soil texture, Estonia	Estonian Land Board 2000
Soil texture, other countries	Hannerz *et al.* 2002
Drainage systems	Estonian Agricultural Board 2012
Population	National Land Survey of Finland 2001

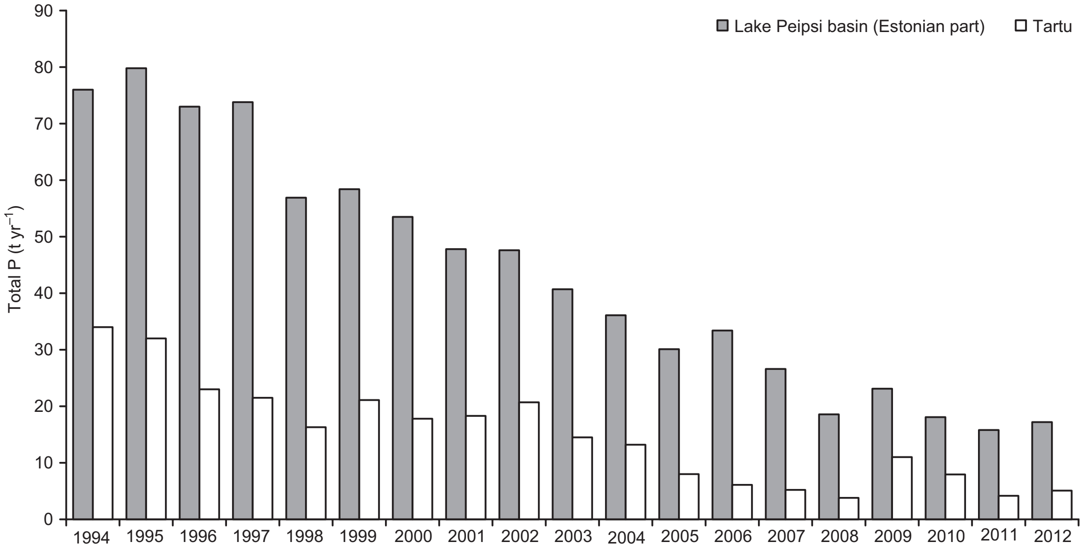

Fig. 3. P load from point sources to surface waters in the Estonian part of Lake Peipsi drainage basin (EEIC 2012a)

areal load was 0.15 kg P km^{-2} . Of the rivers, the largest contributors were the Velikaya (476 t, 66%), flowing from the Russian catchment, and the Emajõgi (134 t, 19%) in the Estonian catchment. Of the point sources, the largest, according to the model, was the city of Pskov, contributing annually 108 t (15% of the gross load), followed bythe town of Ostrov with 17 t (2.4%). Of the total net load, 154 t (21%) originated from natural surfaces: forests, grasslands and wetlands. In total, 298 t (41%) originated from agriculture-dominated land cover types while the remaining 272 t (38%) came from municipal and industrial sources.

The Estonian catchment contributed 200 t (28%) while the Russian and Latvian catchment 523 t (72%, Fig. 5) of the net-load to the lake. In the Estonian catchment, the largest source was agricultural land, contributing 68% of the total Estonian load. In contrast, in the Russian and Latvian catchments, the largest source was municipal and industrial load, contributing 49% of the total load.

Running the 'reference conditions' scenario indicated that 225 t (31%) of total net load was reference load while the remaining 498 t (69%) originated from anthropogenic sources (Fig. 4). Of the total reference load, 77 t (34%) originated from Estonia while the remaining 148 t (66%) came from Russia (Fig 5). The modelled reference concentration of P in the Velikaya, the largest inflowing river, was 0.023 mg l^{-1}. In smaller inflowing rivers, it varied roughly between 0.03 and 0.04 mg l^{-1} (Fig. 6).

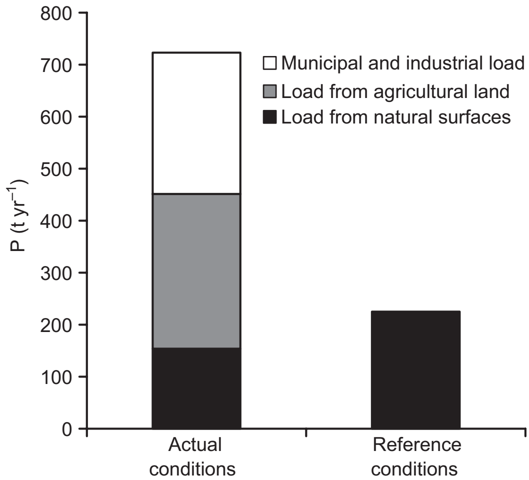

Fig. 4. Actual land-based P load from various sources to Lake Peipsi compared with theoretical reference conditions without anthropogenic pressures and with all land-cover types converted to natural surfaces.

Discussion

The load from natural surfaces in 'reference con-

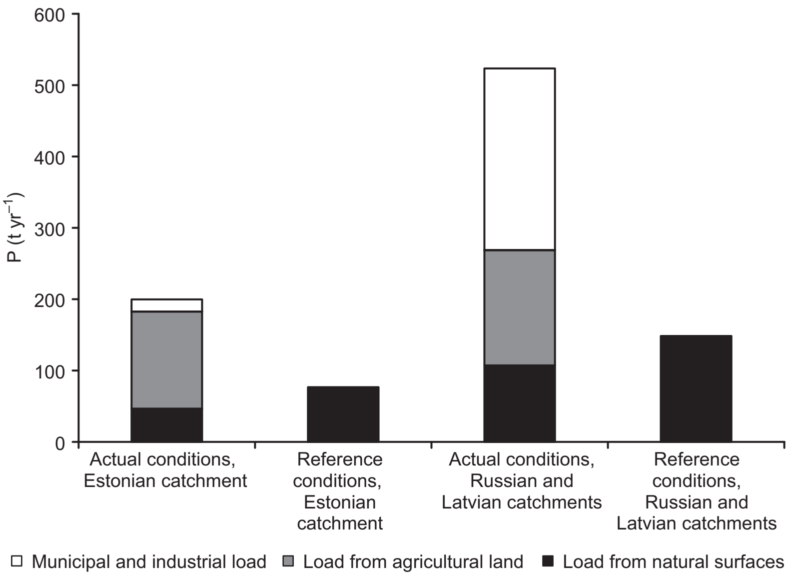

Fig. 5. Actual land-based P load from various sources and countries to Lake Peipsi compared with a theoretical reference conditions without anthropogenic pressures.

ditions' exceeded that load in 'actual (= present) conditions' (Fig 4). This was due to much higher rate of natural surfaces in 'reference conditions' (100%) than in 'actual conditions' (72%). However, as in 'actual conditions' the load from natural surfaces formed only 21% of the total load, human impact obviously significantly facilitates eutrophication of the lake and should be radically reduced.

The Estonian government has set the threshold of good status at 0.025 mg P l^{-1} for the northern part and at 0.05 mg P l^{-1} for the southern part of the lake (Riigi Teataja 2010). Nõges and Nõges (2006) proposed the P limit of good status for the entire lake be 0.028 mg l^{-1}. Nowadays, the concentration of P in Lake Peipsi has a constant spatial pattern, decreasing from the south towards the north. The measured concentration in 2011–2013 in the southern part of the lake, Lake Pihkva, (maximum 0.078 mg l^{-1}, mean 0.076 mg l^{-1}) was almost twice as high as that in the northern part (Lake Peipsi *sensu stricto*, maximum 0.044 mg l^{-1}, mean 0.037 mg l^{-1}). Consequently, in both parts of the lake, the achievement of good status requires the reduction of roughly 40% of the current, average P content. This reduction depends partly on processes occurring between water and sediments in the lake. In a study on 35 various lakes, Jeppesen *et al*. (2005) found that after the reduction of the external load of P to lakes, internal loading from sediments increased during 5–10 years. After that period, however, P concentration in the lake decreased in the same proportion as the external load. We conclude that the long-term target for the reduction of P concentration by 40% requires a decrease of the total, external load (723 t) also by around 40% which amounts to an annual reduction of 289 t (Fig. 4). Since the policy aim is not to control the natural load, these 289 t must be removed from the anthropogenic load, which now amounts to an average of 498 t. Therefore, the achievement of good status requires the reduction of the anthropogenic load by at least 58%.

As the P concentration in target conditions should be 40% lower, the total, annual load should not exceed 434 t. That rate exceeds the reference load by 93%. Adding this 93% to the reference load of both countries, we propose that the maximum acceptable load in the Estonian catchment should amount to 148 t while the acceptable load from the Russian and Latvian side should constitute the remaining 286 t.

The yearly P load form the Estonian part of the catchment should be reduced by at least 52 t as compared with the current average annual load. The corresponding reduction target for Russia is the remaining 237 t.

While more than 90% of the P load originates from diffuse sources on the Estonian side,

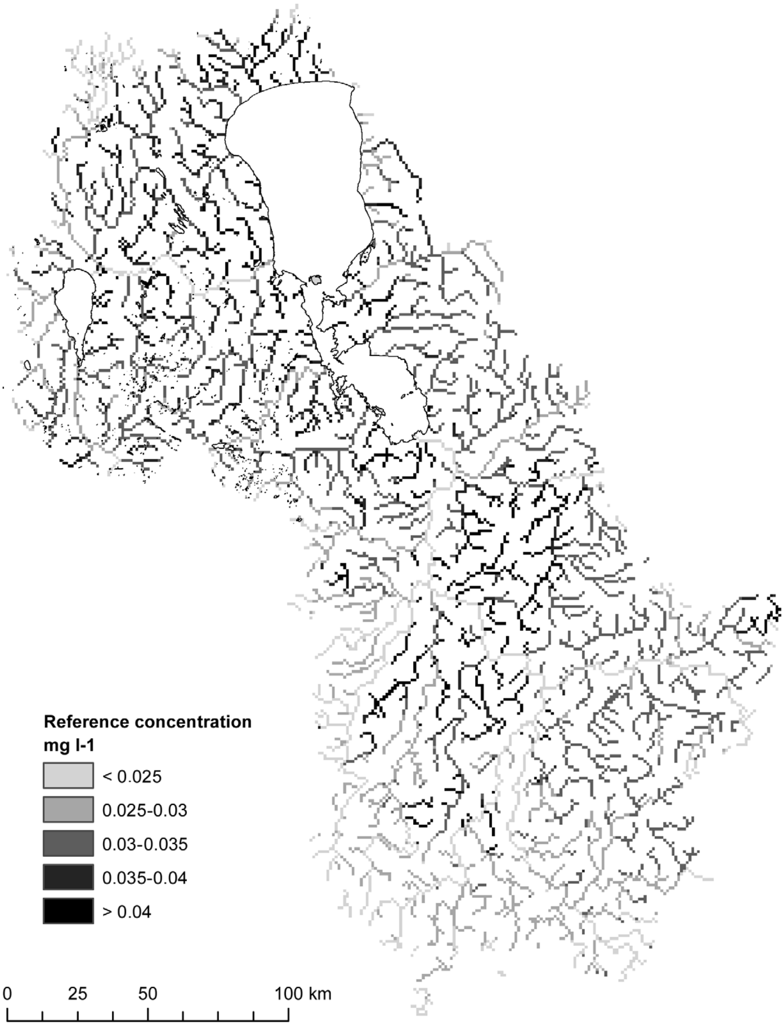

Fig. 6. Reference concentration of P in Lake Peipsi drainage basin.

the Russian P load comes mainly from point sources. Therefore, most of the reduction in Estonia should be achieved by controlling the diffuse load from agriculture as the point sources contribute only 17 t. On the Russian side, the situation is completely different. The agricultural load is not as critical as municipal and industrial loads. The total load from point sources in Russia and Latvia (255 t) exceeds even the total reduction target of 237 t.

Therefore, the Estonian management measures should prioritize land use issues, such as a reduction of diffuse emissions from agriculture. In contrast, Russian policy target should focus on municipal and industrial waste water treatment.

In the light of our findings, the achievement of a 40% load reduction to comply with the legislative requirement would hardly bring the lake to good ecological status. Although the P load reduction target for Lake Peipsi is stringent, the target still exceeds the reference load almost twice. This target, therefore, seems to violate the WFD. On the other hand, WFD should, perhaps, set more realistic requirements.

The results of this study contrast with the findings of Nõges and Nõges (2006) who proposed that the reference level of P concentration for Lake Peipsi should be 0.028 mg l^{-1}. Considering that the mean measured concentration in Lake Peipsi *sensu stricto* in 2011 was 0.044 mg l^{-1}, the corresponding anthropogenic part forms only 36%, e.g. 0.016 mg l^{-1}. This anthropogenic rate was significantly lower as compared with our findings that the share of anthropogenic load in the total load was 69%. Such a difference can be explained by the methodological gap. While our study describes the imaginable conditions of no human impact, Nõges and Nõges (2006) describe the situation in the 1930s, 'before the onset of industrial methods in agriculture and the application of artificial fertilizers'. However, at that time, land cover probably resembled the reference conditions less to the land cover nowadays. Although agricultural land was perhaps less intensively managed, the number of rural inhabitants of Estonia in 1934 was 83% higher than current figures (Statistical Office of Estonia 2014). The P load from scattered dwellings and industries could be significant in that waste water treatment did not exist. Also, Kapanen (2012) reported that the sedimentation process in Lake Peipsi was the highest between 1914 and 1935. The high accumulation of P in that period may reflect extensive drainage and forest clearcuts during that period which, in turn, boosted erosion and the transport of P to the lake. Therefore, setting reference conditions to 1930s may lead to a serious underestimation of the human impact on water bodies.

Similarly, the modelled reference values of P concentration in streams, varying roughly between 0.03 and 0.04 mg l^{-1}, remain significantly lower than those proposed for similar stream types by applying other methods (e.g. Dodds and Oakes 2004, McDowell *et al*. 2013). We conclude that our reported virtual mapping method details the reference conditions by the lowest load and concentration values. However, we understand that the achievement of these values in actual life remains quite unrealistic.

HELCOM Baltic Sea Action Plan (HELOM 2007) targeted to achieve "concentration of nutrients close to natural levels", specifying maximum allowable annual load of P to the Baltic Sea to 21 060 t which formed 74% of total actual load in 2006 (HELCOM 2011). In contrast, source apportionment of P load to the Baltic Sea in 2006 by HELCOM (2011) concluded that the rate of natural background load was only 4540 t (16% of total load). Obviously, there is an inconsistency between the quantification of 'natural background load' and 'maximum allowable load to achieve concentration of nutrients close to natural levels', the latter exceeding the former by 4.6 times. HELCOM (2011) natural background estimate, however, did not involve a theoretical natural background part of load from agricultural and urban surfaces. Assuming that the ratio between 'load from natural surfaces' and 'load in reference conditions' is 0.68 as found in our study, an actual natural background load to the Baltic Sea might be around 6960 t (23%).

Conclusions

This paper demonstrates a novel approach to defining the reference pollutant load for a large water body and reference concentrations without seeking historical land uses, population densities, point and diffuse source pollution. Instead, a theoretical scenario is modelled, presenting what the current totally undisturbed state of the environment would be. In defining such a scenario, land cover was transferred to natural while point pollution sources were erased from the model input maps. The results indicated that the natural load of pollutants to water bodies might be significantly lower and human impact correspondingly stronger than previously estimated.

Yet, this study could not consider other human impacts such as climate change, management of forests, decline of wetlands, etc. Therefore, we could only present here the effects of the most critical human factors. The reference conditions, theoretically envisioning undisturbed waters in the current period, could be further specified.

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